NATURE Conservation

Research Article

Prioritising areas for conservation within Tropical Important Plant Areas of the British Virgin Islands, Caribbean

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Abstract

Oceanic islands are particularly vulnerable to the global decline of biological diversity, suffering disproportionally large losses of endemic species. A primary tool for mitigating species loss is the establishment of protected area networks. The 2030 Global Biodiversity Framework target calls for the protection of 30% of Earth's land surface by 2030. This study identifies areas within the Tropical Important Plant Areas network of the British Virgin Islands (BVI), to better inform the expansion of the current protected area network with the objective of conserving the BVI's unique flora. We identified and applied conservation targets for five threatened habitats and 34 species of conservation concern, including four endemic to the BVI. A total of 5,248 georeferenced plant records for the 34 species collected through decades of collaborative work between the National Parks Trust of the Virgin Islands and the Royal Botanical Gardens, Kew, along with the distribution of five threatened habitats were used within the decision support system MARXAN to identify four spatial portfolios to guide the expansion of the BVI's current protected area network. Highlighting the need to expand the current (2007–2017) Protected Areas System Plan in the BVI, we found that the current Plan only covers 15% of terrestrial land and does not meet the conservation targets for plants and habitats. The portfolios identified in our analysis efficiently expand the current Protected Areas System Plan to strategically expand coverage for all conservation features, with two main portfolios reaching all defined conservation targets for protection. Notably, to evaluate options not requiring land purchase, we extracted areas within state-owned Crown land from two main identified portfolios and found that the two Crown land-portfolios could protect 28% and 23% of the BVI, respectively, while meeting the targets for most plants of conservation concern. However, to reach 30% land protection and meet the conservation targets for all plant species, including endemics, private land would need to be considered for this inclusion within the protected area network. Our results provide science-based guidance for the selection of candidate protected area expansion sites that include threatened plants and habitats for reaching the 2030 Biodiversity Framework targets. While systematic conservation planning can provide guidance on protected area expansion, it is important to evaluate and prioritise conservation

actions, based on multiple solutions and available resources. We recommend similar approaches are applied more broadly throughout the Caribbean and other archipelagos across the world.

Introduction

Anthropogenic demand for space and resources has led to biodiversity loss, primarily driven by habitat loss and land-use changes (Chaudhary et al. 2015). Notably, the Convention on Biological Diversity (CBD) found habitat loss and degradation to be the greatest threats to the world's biodiversity (Secretariat of the Convention on Biological Diversity 2010). Without actions to reduce the drivers behind loss of biodiversity, one million species are at risk of extinction, several within decades and the acceleration of species loss will continue which has been estimated to being ten to a hundred times larger than the average over the past 10 million years (IPBES 2019). Thus, conserving adequate and representative habitat space is one of the most crucial challenges we are faced with in environmental management policies (Tjørve 2010). Threshold estimates have led to the suggestion that conservation action is needed when the amount of remaining functional habitat falls below ~ 30% (Banks-Leite et al. 2014). Responding to this, the 2030 Global Biodiversity Framework sets a minimum conservation target of 30% of Earth's terrestrial, inland water, marine and coastal areas by 2030. It states that areas crucial for biodiversity and ecosystem functions and services should be prioritised. This involves effective conservation as well as management of ecologically representative, well-connected and equitably governed systems of protected areas or employing other effective area-based means (CBD 2022). Despite the expansion of protected areas over the past decades (Johnson et al. 2017), the Protected Planet Report 2020 claimed that terrestrial and inland waters protection stands at 17% of the terrestrial land surface (Bingham et al. 2021), emphasising the need for active measures towards protecting additional land to reach the 2030 Global Biodiversity Framework targets (CBD 2022).

Landscape connectivity is crucial for the exchange of species and genes between habitats (Daigle et al. 2020). The challenge is not only to declare sufficient land for conservation, but also design efficient protected area networks that capture key biodiversity dynamics. Notably, it has been suggested that protected areas that are small, isolated or poorly designed do not perform well when it comes to biodiversity conservation (Dudley and Parish 2006). The question of efficient protected area network design is summarised in the ongoing Single Large Or Several Small (SLOSS) areas debate (Tjørve 2010). Fukamachi et al. (1996) argued that more species could be supported with several small areas, but few large areas could preserve a greater number of rare species. Greater diversity of habitats can be reached with several small areas, but this results in extensive boundary lengths, which can require larger management costs, reduced connectivity and more edge effect (Ball et al. 2009). Edge effect could result in areas becoming more impacted by invasive species and extreme

weather conditions (Saunders et al. 1991) and, in general, edges are unfavourable for a majority of species, although more generalised species benefit from edge effect (Ardron et al. 2010). Ardron et al. (2010) further suggest that compact reserve systems, with less edge-to-area ratio, benefit from a smaller number of reserves, lowering management and transactional costs. These observations underline that there is no single best solution in designing protected area networks and the importance of choosing parameters wisely, as well as prioritising between outcomes, is recommended for effective conservation planning.

Due to the high ratio of endemic species and impacts caused by invasive species, islands are critical places to prioritise conservation and mitigation efforts. Although oceanic islands comprise only 5.3% of the Earth's landmass, they are home to 17% of plant, 19% of bird and 17% of rodent species, resulting in islands having 3.6 times as many species per km^2 than continental areas (Tershy et al. 2015). Importantly, many island species are endemics that are found nowhere else on earth (Whittaker et al. 2017). Moreover, 37% of species listed as Critically Endangered (IUCN 2022) occur on islands (Tershy et al. 2015). However, Whittaker et al. (2017) found that islands have contributed to more than 60% of the global terrestrial species extinction since 1500 CE.

The Caribbean Region is considered a global biodiversity hotspot, with many endemic species and large rates of habitat loss (Myers et al. 2000). The British Virgin Islands (BVI) lies within the Puerto Rican Bank Floristic Province, interconnecting the Greater Antilles and the southern inner arc volcanic islands of the Lesser Antilles (Dalsgaard et al. 2014). The BVI stretches over 153 km^2 and consist of more than 50 rocks, cays and islands, of which 16 are populated. Most of the human population in the BVI live on Tortola, which is also the largest island, with the highest peak, Sage Mountain, rising to an altitude of 543 m (The BVI TIPAs National Team 2019b). In area, Tortola is the largest (57 km^2) followed by Anegada (40 km^2) and Virgin Gorda (22 km^2) (The BVI TIPAs National Team 2019a). In September 2017, the BVI experienced catastrophic damage from category five Hurricane Irma, which emphasised the need to account for climate change mitigation when designing protected area networks (Gore et al. 2019). The BVI has approximately 648 native plant species, including four endemics. Many plant species in the BVI are threatened (Dani Sanchez et al. 2021) and face several threats, including invasive species, pests and diseases, grazing and urbanisation (Bárrios et al. 2021). In addition, island species are under greater pressure in coastal areas due to land clearing activities to accommodate expanding human needs, as sea levels rise (The BVI TIPAs National Team 2019b). The four endemic plant taxa on the BVI are: *Vachellia anegadensis* (Britton) Seigler and Ebinger, *Metastelma anegadense* Britton, *Pitcairnia jareckii* Proctor and Cedeño-Mald. and *Senna polyphylla* var. *neglecta* H.S. Irwin and Barneby (The BVI TIPAs National Team 2019a; Bárrios et al. 2021). All four endemics face extinction risk in the wild (IUCN Standards and Petitions Committee 2019).

To advance the identification and protection of Important Plant Areas (IPAs) in tropical regions and mobilise both current and newly-acquired plant data, The Tropical Important Plant Areas (TIPAs) programme (https://www.kew.org/science/our-science/projects/tropical-important-plant-areas) was launched in 2015 (Darbyshire et al. 2017). In 2018, a total of 18 TIPAs were identified within the BVI, based on decades of joint botanical activity between the Royal Botanic Gardens, Kew and the National Parks Trust of the Virgin Islands (Dani Sanchez

et al. 2021). The identification of TIPAs within the BVI provides a framework for shaping future policies and providing information for the protection and conservation of regional and national biodiversity, as well as endemic plant species and their habitats (The BVI TIPAs National Team 2019a). Although the BVI has declared 21 terrestrial National Parks, the identification of TIPAs showed that most native flora are under-represented within the current protected area network (The BVI TIPAs National Team 2019b; Dani Sanchez et al. 2021). Dani Sanchez et al. (2021) further argued that as the TIPAs network was both too large to have all areas protected and that some TIPAs were on private lands, further analysis should be conducted to find areas within the TIPAs to declare as protected areas.

One way of expanding protected area networks is through the six-step approach of systematic conservation planning (Margules and Pressey 2000; Wiersma and Sleep 2016). The first three steps provide information for the expansion of protected areas, by firstly collecting biological data, secondly identifying conservation goals and conservation features and thirdly by reviewing the performance of the current areas. The fourth step is the actual reserve selection. The final steps are to implement the conservation actions and provide on-going maintenance (Margules and Pressey 2000; Wiersma and Sleep 2016). The reserve selection practice can be done with various decision-support systems and reserve-selection algorithms, where MARXAN (Ball et al. 2009) is believed to be the most used worldwide, both for terrestrial and aquatic ecosystems (Ardron et al. 2010; Schill and Raber 2011; Wiersma and Sleep 2016). MARXAN has been used in the designation of the marine protected areas of the BVI and protected areas in Jamaica, as well as the wider Caribbean Basin (Huggins et al. 2007; McPherson et al. 2008; Woodfield-Pascoe et al. 2013). MARXAN identifies the overall best or most efficient portfolio of planning units (Huggins et al. 2007), while seeking to meet conservation goals and minimise costs (Schill and Raber 2011). Systematic conservation planning using MARXAN can, thus, help design a biologically-resilient and redundant network of protected areas.

This study supports the 2030-Global Biodiversity Framework (CBD 2022) by identifying important areas for expanding terrestrial protection within the TIPAs of the BVI, based on a synthesis of a comprehensive species dataset and habitat maps that are integrated into the MARXAN reserve selection tool. As suggested by Cowling et al. (2003), our study intertwines expert knowledge and algorithms into conservation practice and, as suggested by Dani Sanchez et al. (2021), we provide information for the expansion of the protected areas of the BVI within the TIPAs. Our results have implications for the conservation of Caribbean biodiversity and will guide the strategic expansion of new protected areas across the BVI and thereby help conserve threatened plant species, including the BVI's four endemic plant taxa.

Methods

Conservation features and targets

We selected 34 plant species and five threatened habitats as conservation features for the analysis. The 34 plant species originated from a list of 35 Species of Conservation Concern as defined by the UKOTs Team (2021), based on their restricted range and endemism (The BVI TIPAs National Team 2019a; Dani San-

chez et al. 2021) which were used for the identification of TIPAs in the BVI. One plant species, *Picrasma excelsa* (Sw.) Planch., had no recorded locations, thus the analysis did not consider this species. For the 34 Species of Conservation Concern, a total of 5,248 high accuracy (+/- 10 m) georeferenced location records were included in the analysis (Appendix 1: Table A1). Data were available for terrestrial seed plants only. All plant records were treated as presence/absence data, as the population size was not available for all records. For full details on data collection, see Dani Sanchez et al. (2021).

In addition to geographical plant records, we examined five threatened habitats. The BVI national list of threatened habitats consists of coastal shrubland, dry salt flats, mangrove, semi-deciduous gallery forest and upland evergreen forest (The BVI TIPAs National Team 2019a). These habitats meet the TIPAs criteria of being either natural or semi-natural habitats that support higher vascular plants and each currently cover less than 10% of BVI terrestrial land or is present in three or fewer islands (Darbyshire et al. 2017). Further, to be considered a threatened habitat, a continuous decline of the habitat has to have been observed, estimated, inferred or projected for the BVI (The BVI TIPAs National Team 2019a). Threatened habitats were mapped using QGIS (QGIS.org 2021) from two satellite-derived land-cover datasets: (1) The BVI Habitat map 2020 (Scarth and Pike 2020) derived from Sentinel-2 imagery was used primarily, due to its high spatial resolution of 10 × 10 m; (2) the Landsat-7 dataset in Kennaway et al. (2008) with a 30 × 30 m spatial resolution was used for the semi-deciduous gallery forest class as it was not present in The BVI Habitat map 2020.

Authors from the British Virgin Islands TIPAs National Team and University of Copenhagen held workshops to determine conservation targets for all conservation features (a percentage to protect for each plant population or habitat extent), making use of their collective practical knowledge on the conservation features, their spatial distributions and levels of threat. The threatened habitats were assigned a conservation target of 30% each in accordance with the 2030 Global Biodiversity Framework (CBD 2022). Targets for each conservation feature are shown in Appendix 1: Tables A1, A2.

Reserve selection through MARXAN

We investigated where to strategically expand the current protected areas of the BVI within the boundaries of the TIPAs (The BVI TIPAs National Team 2019b; Dani Sanchez et al. 2021), using the decision-support system MARXAN (Ball et al. 2009). MARXAN seeks to identify near optimal solutions through a simulated annealing algorithm, by selecting areas (portfolios of planning units) that efficiently achieve conservation targets, while minimising costs (Ball et al. 2009). The cost parameters were provided by an overall boundary length and an Environmental Risk Surface (ERS; see below). The boundary length is controlled by setting a Boundary Length Modifier (BLM), which allows the user to change the compactness of the final solutions and thereby address the SLOSS approach (Ardron et al. 2010). Lower BLM values will result in the BLM to have less influence and, therefore, select portfolios with increased fragmentation (Schill and Raber 2011). It is important to note that since MARXAN applies a simulated annealing algorithm, it produces several near-optimal solutions (portfolios of planning units to protect) and a summed solution, rather than one

single best solution. In terms of practical conservation planning, these portfolios would then have to be evaluated with respect to practical and/or political perspectives (Ball et al. 2009).

Planning units and MARXAN analysis

A grid of planning units with a size of 30 × 30 m was used, based on the fine scale of available input data (accuracy of +/- 10 m) and the relatively small land areas of the BVI and the TIPAs, making a compromise between data scale and practicality of implication and management (Schill and Raber 2011; Mo et al. 2019). We used the borders of the BVI Habitat map 2020 (Scarth and Pike 2020) to create the grid surface of planning units, removing only the Open water class to cover all land areas of BVI, as well as mangrove habitats. No planning units were clipped to the coastlines nor political boundaries within the BVI, as this would result in small, fragmented planning units. The final area of planning units covering the BVI (~ 166 km^2) was, therefore, slightly larger than the official land area of the BVI (~ 153 km^2) (The BVI TIPAs National Team 2019b).

In order to design a biologically resilient network of protected areas, the planning units were divided into three geographic strata, named after the largest islands in each specific strata: Anegada, Tortola and Virgin Gorda (Fig. 1). The introduction of these strata, as opposed to running MARXAN on all of the BVI at once, were used to drive the optimal portfolio selection across the archipelago rather than being centred in a single area of the BVI. This design follows the previous marine protected area analysis within the BVI, which also employed three strata to force the selection of conservation features beyond Anegada's large reef system (Woodfield-Pascoe et al 2013). Similarly, the use of strata in a terrestrial planning context would influence portfolio selection beyond Anegada's rich terrestrial biodiversity. The use of strata also allowed different application of adaptive targets to plants which were more abundant in one stratum than another. MARXAN was run individually on each stratum and results were combined into collective portfolios for all of the BVI. A total of 184,791 planning units were analysed and assigned a status of "available" for MARXAN selection if they fell within the TIPAs boundaries and a status of "unavailable" for those outside the TIPAs boundaries. This allowed the prioritisation of areas within TIPAs for future protection. Planning units already part of the Protected Areas System Plan were assigned a "locked" status to ensure inclusion in the portfolios. Each planning unit was assigned a cost provided by an ERS (see below). For each planning unit, we calculated the total amount of each conservation feature within, either in number of occurrences (plant taxa) or area (habitats).

Protected area solutions that are too fragmented can be difficult to implement and are ecologically less functional. Following a BLM sensitivity analysis, we settled on a BLM value of 0.1. This achieved an optimal degree of planning unit clustering and delivered a smaller total area with accepted initial coverage and connectivity. For each of the three strata of the BVI, 100 runs were executed using 1,000,000 iterations per run. MARXAN generates two standard outputs: the best solution, as well as a summed solution. The best solution portrays the portfolio of planning units with the lowest cost score, found in all the good combinations of planning units (portfolios) selected by MARXAN (Ball et al 2009). As we executed 100 runs, the best solution was found within one of these. The

latter portrays the selection frequency, i.e. the number of times each planning unit was selected in each of the 100 runs, which Ardron et al (2010) suggests being one of the most useful outputs. We therefore examined two main portfolios of planning units; (1) the best solution output (hereafter 'Best Solution'); (2) the planning units with a selection frequency of a 100, thus a portfolio of planning units that were selected in each of the 100 MARXAN runs (hereafter 'SF100'). From those portfolios, we extracted two Crown land portfolios: (3) the best solution output that fell within Crown lands, thus not private land (hereafter 'Best Solution CL'); and (4) the planning units with a selection frequency of 100 that fell within Crown lands (hereafter 'SF100 CL'). The extraction of overlapping areas within the main portfolios and Crown land allowed us to examine portfolio areas that would not require land purchase. Planning units within the current Protected Areas System Plan were included in all four portfolios.
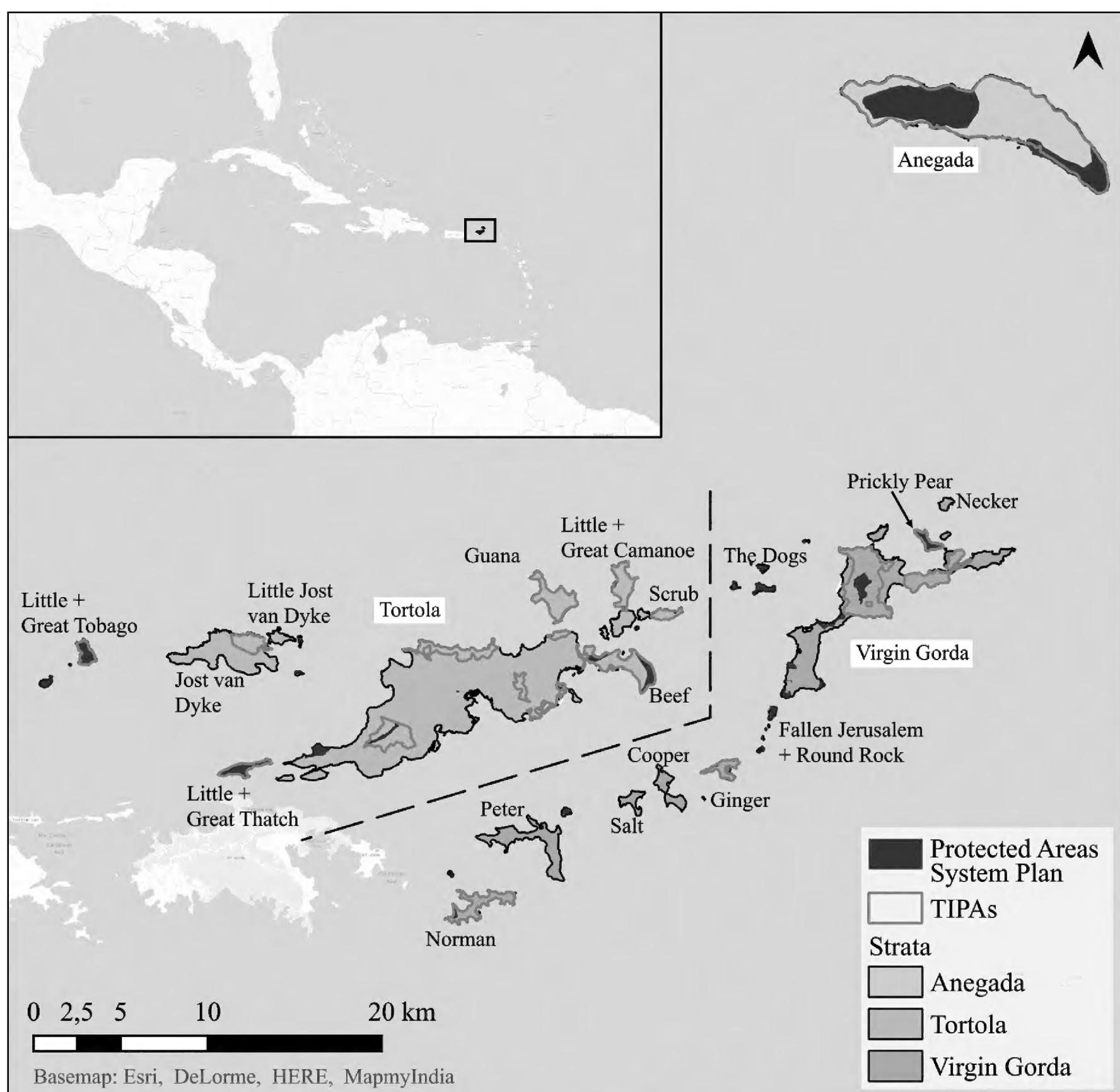
Figure 1. Study area. Reference map showing the location of the BVI in the Caribbean Sea, as well as the strata division, named after the largest island in each specific area: Anegada; Tortola; and Virgin Gorda. Tropical Important Plant Areas (TIPAs) are shown, as well as areas within the current Protected Areas System Plan. A dashed line is added to show the distinction between islands allocated to the Tortola and Virgin Gorda strata.

Environmental Risk Surface as a cost parameter

To estimate the level of threat to the conservation features and to provide MARXAN with a cost parameter beside the BLM, an Environmental Risk Surface (ERS) was produced to assign a cost value to each planning unit under consideration (Schill and Raber 2011). We assessed the locations of possible threats to biodiversity (e.g. an airport). The threats were drawn as polygons in GIS using a combination of OpenStreetMap layers (OpenStreetMap contributors 2021), the BVI Habitat map 2020 (Scarth and Pike 2020) and ground reference information acquired from Google Maps satellite imagery (Google 2021a, b), to capture the outlines of the threat features. Each threat was assigned an intensity score and an influence distance (Appendix 2: Table A3, Fig. A1). The latter expresses the intensity of the threat outside the immediate area, with the intensity decreasing the further away from the threat, until it no longer poses a threat to the conservation features. We examined two published assessments that applied the ERS methodology in Jamaica (McPherson et al. 2008) and across the Caribbean (Huggins et al. 2007) to understand the relationships between threat intensity scores and decay distances. In MARXAN, all costs are seen in relation to the other costs, so intensity scores in the modelled ERS are within a relative scale (Schill and Raber 2011). We selected four levels of intensity scores within the range of 0–99: 99 (high), 66 (medium), 33 (low) and 10 (very low). The scale was chosen to reflect fractions of thirds, followed by a lower intensity score of 10 to quantify the lower intensity for agriculture (Huggins et al. 2007; McPherson et al. 2008). To ensure MARXAN only selected planning units that were crucial for the portfolios, the minimum cost was set to a very low, non-zero, value (e.g. 0.01) to all planning units that did not overlap with the ERS modelled values. For each individual threat feature, multiple buffers were drawn outside the borders, until they reached the length of the defined decay distance. For each threat feature with multiple buffers, each buffer was assigned intensity scores from the aggregation of intensity scores and decay distances of the threat and the specific buffer's distance to the threat, with the outermost buffer having the intensity score closest to zero. The ERS layer was turned into vector points in GIS, reflecting the grid surface of 30 × 30 m, with the maximum intensity score assigned for overlapping buffer values. The vector points were ultimately joined to the planning units as cost values.

Results

We identified two main portfolios covering 39% ('Best Solution) and 32% ('SF 100') and two Crown land portfolios covering 28% ('Best Solution CL') and 23% ('SF 100 CL') of the total area of the BVI planning units of 166.3 km², respectively (Fig. 2, Table 1; Suppl. materials 1–3). It was possible to reach all defined conservation targets during the analysis for the two main portfolios, 'Best Solution' and 'SF100'. Protection of individual conservation features improved for all four portfolios of planning units compared to the current Protected Areas System Plan, which covers 15% of the total area of the BVI (Table 1).

The current Protected Areas System Plan of the BVI meets the conservation target for only 12 plant species and two habitats, but meets none of the targets for endemic species. The current plan covers 15% of the terrestrial land area of

the BVI and 31% of the combined area of threatened habitats. The main 'Best Solution' and 'SF100' portfolios both cover more than 30% of the BVI (39% and 32%, respectively). Despite the 'Best Solution' including more planning units than 'SF100', the two main portfolios covered the exact same species and threatened

The British Virgin Islands
- Crown Land
- Protected Areas System Plan
- Islands

Portfolios
- 'Best solution'
- 'SF100'

0   2,5   5   10   16 km
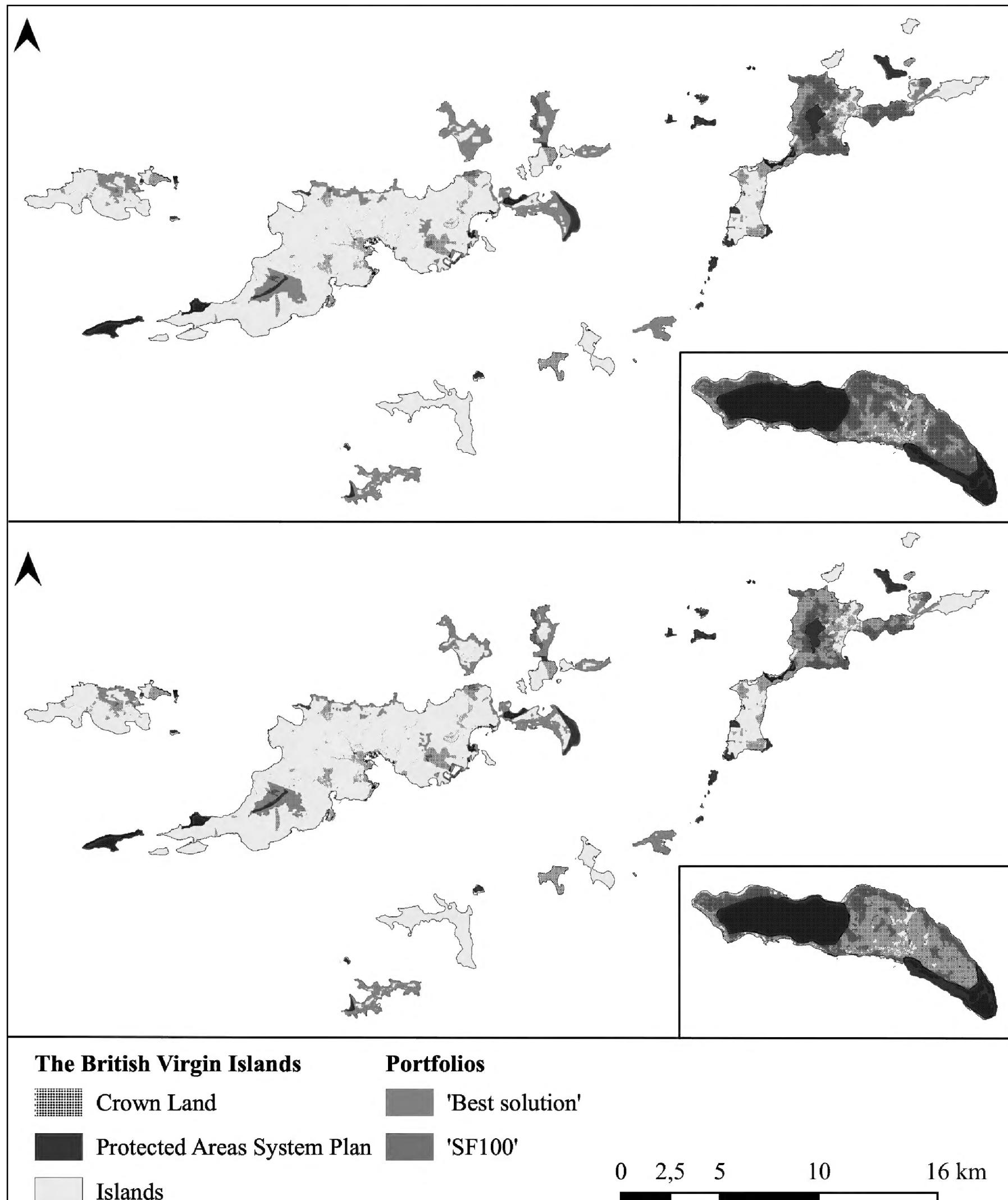
Figure 2. MARXAN portfolios. Maps showing portfolio results for the 'Best Solution' (top) and the planning units with a Selection Frequency of a 100; 'SF100'(bottom). The 'Best Solution' cover almost 10 km² more than 'SF100', adding up to 39% and 32% of the BVI, making both portfolios successful in reaching the 2030 Global Biodiversity Framework targets of protecting 30% of the land surface (CBD 2022). See also Suppl. materials 1−3 for a higher resolution overlap between the two portfolios portrayed for each of the three strata of Anegada, Tortola and Virgin Gorda, respectively.

Table 1. Portfolio analysis. The targets met within the four portfolios compared to the current Protected Areas System Plan. The four portfolios were: (1) 'Best Solution', (2) 'SF100', i.e. the planning units selected in all 100 MARXAN runs, (3) 'Best Solution CL', i.e. the overlapping planning units between the best solution and Crown land and (4) 'SF100 CL', i.e. the overlapping planning units between the 'SF100' portfolio and Crown land. The total area of planning units covering the BVI was 166.3 km^2. One record of the endemic *Zanthoxylum thomasianum* was found outside the TIPAs on Tortola and could, therefore, not be selected by MARXAN. Thus, this species did not reach its target of a 100% coverage within the Tortola stratum. However, as the gap made up by this record is very small and could not be protected within the means of this analysis, we still treated it as a 100% coverage for all endemic species.

Portfolio analysis	Protected Areas System Plan	Main portfolios		Crown land portfolios	
		Best Solution	SF100	Best Solution CL	SF100 CL
Size of portfolios					
Area (km^2)	25.4	64.1	53.3	45.7	37.8
Percentage of BVI	15	39	32	28	23
Conservation features covered by portfolios (%)					
Plant records (n)	26	90	90	70	70
Endemics plant records (n)	30	100	100	95	95
Combined area of threatened habitats	31	62	62	44	44
Number of conservation features where conservation targets were met					
Plant Species of Conservation Concern	12	34	34	27	27
Endemics	0	4	4	1	1
Habitats	2	5	5	4	4

habitats (Table 1; Appendix 3: Tables A4, A5). Notably, the 'Best Solution' and 'SF100' cover 90% of all plant records and 62% of the total area for threatened habitats. Both main portfolios reached the conservation targets for all plant taxa and all threatened habitats. When considering the Crown land portfolios, a total of 27 plant taxa, including the endemic *Vachellia anegadensis* and four threatened habitats met their conservation targets. Conservation feature coverage fell to 70% of all plant records and 44% of the total area for threatened habitats. Coverage for eight plant species did not change (Appendix 3: Table A6).

Many conservation features exceeded their conservation targets. For example, 14 plant species in the main portfolios, 'Best Solution' and 'SF100', exceeded their targets greater than 50%, compared to four plant species within the Crown land portfolios (Appendix 3: Table A6). All habitats reached their 30% targets within the main portfolios. Notably, mangrove and salt-pond habitats exceeded their targets by more than 50 percentage points; however, both were already sufficiently represented within the current Protected Areas System Plan (Appendix 3: Tables A5, A6; for example, salt pond was already protected by 94.7% in the current Protected Areas System Plan). This was also the case for 10 plant species, which increased their representation within the main portfolios, even though these targets were already met within the current Protected Areas System Plan (Appendix 3: Table A6). Table 2 elaborates on 10 conservation features that either did not reach their overall targets or failed to reach their targets within the Crown land portfolios.

One conservation feature (*Zanthoxylum thomasianum*) failed to reach its full targets within the main portfolios (Table 2, Appendix 3: Tables A4–A6). *Z. thomasianum* had different targets depending on its location within the BVI and it failed to cover one plant record, which fell outside the TIPAs; however, in the summed results (Table 1), the gap was treated as achieved. Within the

Table 2. Conservation gaps for features that failed to reach their targets within two or four portfolios. The conservation gaps are shown for the current Protected Areas System Plan (current) and the portfolios. Gaps to meet conservation targets are presented once for the main portfolios and once for Crown land portfolios, as they covered the same conservation targets. A negative gap represents the percentage points needed to reach the conservation targets, while a positive gap represents the percentage points that exceed the target. Species with different conservation targets assigned for different strata of the BVI have the relevant stratum indicated in brackets. The IUCN threat status is listed for all plant species (IUCN 2022).

Species (strata of BVI)	IUCN status	Current	Main Portfolios	Crown land portfolios
		Gap (%-point) for portfolios		
Abutilon virginianum Krapov.	EN	-46	4	-36
Guaiacum officinale L. (Anegada)	EN	47	80	80
Guaiacum officinale L. (Tortola)	EN	-70	30	-70
Machaonia woodburyana Acev.-Rodr. (Tortola)	EN	-41	0	-41
Machaonia woodburyana Acev.-Rodr. (Virgin Gorda)	EN	-50	37	18
Metastelma anegadense Britton (Anegada)	EN	-8	60	55
Metastelma anegadense Britton (Virgin Gorda)	EN	-100	0	-75
Miconia thomasiana DC.	NT	-4	70	-4
Pitcairnia jareckii Proctor & Cedeño-Mald.	EN	-10	84	-10
Sabal causiarum (O.F.Cook) Becc. (Anegada)	VU	-90	0	0
Sabal causiarum (O.F.Cook) Becc. (Tortola)	VU	-34	2	-34
Zanthoxylum thomasianum Krug & Urb. (Tortola)	EN	-100	-2	-75
Zanthoxylum thomasianum Krug & Urb. (Virgin Gorda)	EN	-52	38	-25
Upland evergreen forest		-20	13	-10

Crown land portfolios, a total of nine conservation features (eight plant species and one habitat) did not reach their targets. We further note with emphasis on IUCN status, that the two Critically Endangered taxa *Myrcia neokiaerskovii* and *Senna polyphylla* var. *neglecta* (IUCN 2022) reached their conservation targets for all portfolios (Appendices 1, 3: Tables A1, A4).

Discussion

Analysis of the four portfolios

Based on the four resulting portfolios, we found that, by expanding the current Protected Areas System Plan to the main portfolios: 'Best Solution' and the 'SF100', it is possible to reach the conservation targets for all conservation features and meet the 2030 Global Biodiversity Framework commitments for the BVI terrestrial land. The 'SF100' portfolio resulted in a more fragmented and scattered selection of planning units; however, both portfolios covered the same conservation features, suggesting that the additional planning units selected within the 'Best Solution' may only improve connectivity. The additional two Crown land portfolios, which extracted overlapping areas between the main portfolios and Crown land, allowed us to evaluate whether it would be possible to meet conservation targets on areas that do not require land purchase, as approximately 80% of land in the BVI is privately owned. Our results show that we can achieve the 2030 Global Biodiversity Framework targets by solely expanding protected areas into Crown land, although private land would be needed to achieve the conservation targets for all plants, including three of the four BVI endemics (Tables 1, 2). All individual habitat types

met their 30% protection targets within the main portfolios; however, this was not the case for the Crown land portfolios as the target was not reached for upland evergreen forest. This further suggests that, to protect 30% of all threatened habitats, protected areas need to expand beyond existing Crown lands. Regardless, the four portfolios offer a significant improvement in protection for all conservation features when compared to the current Protected Areas System Plan and provide evidence and a robust framework for guiding Protected Area expansion.

Many conservation features exceeded their conservation targets (14 plant species and two threatened habitats exceeded their targets by over 50 percentage points) within the main portfolios, as well as four plant species and one habitat within the Crown land portfolios (Appendix 3: Table A6). Although mangrove and salt-pond habitats had already met their targets within the current Protected Areas System Plan, their selected extent also increased within the four portfolios, as well as that for 10 plant species (Appendix 3: Table A6). Given that the primary objective of MARXAN's selection algorithm is efficiency, there is a high likelihood that multiple rare occurrences of conservation features within a planning unit or across neighbouring planning units will be included in the final portfolio. When these conservation features are clustered together in close proximity, the selection of neighbouring planning units can result in targets being exceeded.

Interdisciplinarity between algorithms and experts

If a perfect solution based on perfect input data and variables existed, it might not be the best solution possible due to local politics, land ownership, funding for purchase, stakeholder involvement or current and future land use. MARXAN solutions provide decision support and should be vetted and combined with expert and local stakeholder knowledge to arrive at a solution to implement. This approach is endorsed by Cowling et al. (2003), who suggest the use of systematic conservation planning algorithms should be closely integrated with expert knowledge to combine the strengths of both approaches. The review of MARXAN portfolios by local experts can provide valuable specific insight into landscape context, political environment, biodiversity knowledge and management issues that are not likely captured in a MARXAN portfolio selection (Cowling et al. 2003). Ardron et al. (2010) stated that MARXAN should be used to model a suite of alternative protected area network designs for stakeholders to review and select from, as opposed to giving one definite solution. This is why it is important to model a variety of scenarios whose input parameters originate from stakeholder workshops. Portfolio results should then be presented and reviewed by experts and stakeholders, having the most appropriate portfolio selected or modified.

Prioritising areas for conservation within the TIPAs

TIPAs are often used as a way to highlight protected area gaps and have been used in other areas of the world. Couch et al. (2019) mapped 22 TIPAs in Guinea, West Africa occupying 3.5% of Guinea's land surfaces, highlighting areas of irreplaceable plant diversity and the need to protect against species extinction. Not all 22 areas were protected at the time, although it was stated that if all 22 TIPAs were protected, a vast amount of Guinea's wild plant resources would be safeguarded, including over 60% of threatened plant species and a majority of species and rep-

resentative areas for nine threatened habitats found across Guinea (Couch et al. 2019). As suggested by The BVI TIPAs National Team (2019a), the integration of the TIPAs into a revised Protected Areas System Plan would be beneficial for the conservation of the 34 Species of Conservation Concern and threatened habitats. Some TIPAs are entire islands or cover large parts of private land and further assessments on these areas within the TIPAs Network are needed to protect a critical percentage of conservation features. Addressing this, the four portfolios presented in this study highlight areas within the TIPAs, where conservation efforts should be prioritised to adequately manage and promote species preservation. Our work provides a science-based framework towards guiding the expansion and subsequent implementation of conservation efforts for the 34 plant species and the five threatened habitats, based on the areas selected for TIPAs (Dani Sanchez et al. 2021) and the Protected Areas System Plan 2007–2017 (Gardner et al. 2008).

Our portfolio results need to be presented as options for experts to review, modify and implement (as per Cowling et al. (2003)). Stakeholders from the National Parks Trust of the Virgin Islands (NPTVI) and Kew need to carefully assess our results and integrate them into a strategic conservation planning design for resource management implementation at relevant scales (Huggins et al. 2007). The Crown land portfolios presented in this work demonstrate how a large number of conservation targets can be achieved without focusing on areas that require land purchase. A recommended first step would be to evaluate areas for conservation within the Crown land portfolios, followed by prioritisation outside Crown lands, paying special attention to conservation features that did not meet their targets, as well as the planning units selected in each MARXAN run; the 'SF100' portfolio. Notably, the protection of the BVI endemic plant species would require voluntary partnerships with BVI private landowners. Private protection is possible under the Virgin Islands National Parks Act (Virgin Islands National Parks Act 2006) conservation agreements or under the Virgin Islands Physical Planning Act (Virgin Islands Physical Planning Act 2004) that can protect species within declared Environmental Protection Areas. Moreover, Ball et al. (2009) recommended that planning units identified as having both high selection frequency and a high cost are under immediate threat and should be considered priority areas where closer examination is warranted. Further, in cases where land purchase is not possible, areas could still be recognised within the Protected Areas System Plan as OECMs (other effective area-based conservation measures; IUCN-WCPA Task Force on OECMs (2019)) by engaging with private landowners to promote conservation actions and focused management within their lands.

When expanding protected area networks, we note that management effectiveness guided by a management plan is critical for protected areas to be successful tools for biodiversity conservation (Geldmann et al. 2013). The first target of the 2030 Global Biodiversity Framework focuses on integrating areas in biodiversity-inclusive spatial planning and other effective management activities, to ensure that loss of areas of high biodiversity value is brought close to zero, with respect for local communities and indigenous people (CBD 2022). Watson et al. (2014) stated how a lack of resources, most notably in developing countries, was the primary driver behind weakened performance of protected areas. As protected areas continue to expand, these areas are likely to have increased contact with local communities, which may lead to conflicts (Gooden and 't Sas-Rolfes 2020). Further, in 2003, CBD found that only 6% of involved countries reported to have adequate resources for

carrying out protected area management (Watson et al. 2014). Therefore, we suggest that conservation efforts and any plans to expand protected areas should be followed by an evaluation of adequate resource availability to carry out recommended management actions once the protected areas have been established.

Conclusion

In summary, we demonstrated a science-based and stakeholder-driven framework that identified a representative and efficient protected area network design specific for conserving the unique flora that exists within the British Virgin Islands (BVI). As the BVI is home to 35 plant Species of Conservation Concern (34 with geographical records and, thus, a part of this study), including four which are endemic to the BVI, this work provides a critical foundation to strategically guide decisions on where to expand the current network of protected areas in the BVI. We analysed four portfolios, of which, the two main portfolios fully achieved the conservation targets. It is important to note that the proposed areas within the two portfolios might not be realistically possible to protect due to legal circumstances and resources, such as private ownership. Therefore, we presented two Crown land portfolios, to identify areas within the portfolios that would not require land purchase. However, the number of species and habitats for which conservation targets were met, decreased and most endemics were not well protected under such portfolios. Thus, if all targets are to be met in accordance with the 2030 Global Biodiversity Framework targets (CBD 2022), private areas outside Crown land should be included in a new Protected Areas System Plan or private conservation actions be independently taken if land purchase is not possible. As required by all protected area expansion planning efforts, further assessments and collaboration with stakeholders is recommended to review, approve and implement the necessary conservation efforts. Given the current protected area gaps in the existing Protected Area Systems Plan, our portfolios provide timely insight for conservation decision-makers to act on expanding protection to areas that are urgently needed to safeguard and conserve the rich and unique floral diversity heritage of the BVI. Our approach to evidence-based protected area expansion has wider relevance to the Caribbean Region and the global conservation community, providing a useful template to support nations in their quest to conserve their unique floras and meet international biodiversity commitments.

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Additional information

Conflict of interest

The authors have declared that no competing interests exist.

Ethical statement

No ethical statement was reported.

Author contributions

Each of the authors has fulfilled the following: (1) Contributed significantly to the conception or design of the study; or data acquisition, analysis or interpretation; (2) Participated in drafting the manuscript or provided critical revisions to enhance its content; (3) Given approval for the publication of the final version; and (4) Committed to being responsible for all aspects of the work, ensuring that any enquiries regarding the accuracy or integrity of the work are thoroughly investigated and resolved.

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Data availability

Data were obtained with approval from Virgins Islands Government via the National Parks Trust of the Virgin Islands and Royal Botanic Gardens, Kew. The plant occurrence data used in these analyses were collected over many years by staff of the National Parks Trust of the Virgin Islands and the Royal Botanic Gardens, Kew in collaboration with our regional partners. The complete datasets used are not publicly accessible, in order to safeguard the precise locations of threatened species. Vetted data for the TIP-As can be found on https://tipas.kew.org.

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Appendix 1

Table A1. Conservation features and conservation targets for Plant Species of Conservation Concern.

Species	ID†	IUCN status	Records	Target %
Abutilon virginianum Krapov.	1	EN	83	50
Agave missionum Trel.	2	VU	449	40
Anthurium x selloum K.Koch	3	N/A	17	20
Argythamnia stahlii Urb.	4 (A)	VU	109	20
Argythamnia stahlii Urb.	4 (T)	VU	4	30
Cedrela odorata L.	5	VU	2	50
Croton fishlockii Britton	6	NT	410	20
Erythrina eggersii Krukoff & Moldenke	7	EN	13	50
Galactia eggersii Urb.	8	NT	68	20
Guaiacum officinale L.	9 (A)	EN	18	20
Guaiacum officinale L.	9 (T)	EN	1	70
Ilex urbaniana Loes. ex Urb.	10	VU	23	60
Leptocereus quadricostatus (Bello) Britton & Rose	11	EN	35	100
Machaonia woodburyana Acev.-Rodr.	12 (T)	EN	17	100
Machaonia woodburyana Acev.-Rodr.	12 (VG)	EN	169	50
Malpighia woodburyana Vivaldi	13	VU	304	20
Maytenus cymosa Krug & Urb.	14	EN	186	60
Metastelma anegadense Britton	15 (A)	EN	212	40
Metastelma anegadense Britton	15 (VG)	EN	4	100
Miconia thomasiana DC.	16	NT	53	30
Mitracarpus polycladus Urb.	17	EN	48	70
Myrcia neokiaerskovii E.Lucas & K.Samra	18	CR	59	100
Myrcia neothomasiana A.R.Lourenço & E.Lucas	19	EN	34	60
Peperomia wheeleri Britton	20 (T)	EN	1	100
Peperomia wheeleri Britton	20 (VG)	EN	38	40
Pilea sanctae-crucis Liebm.	21 (T)	EN	21	40
Pilea sanctae-crucis Liebm.	21 (VG)	EN	3	100
Piptocoma antillana Urb.	22	LC	40	10
Pitcairnia jareckii Proctor & Cedeño-Mald.	23	EN	16	10
Psychilis macconnelliae Sauleda	24	NT	78	20
Reynosia guama Urb.	25	NT	207	10
Rondeletia pilosa Sw.	26	NT	106	10
Sabal causiarum (O.F.Cook) Becc.	27 (A)	VU	10	100
Sabal causiarum (O.F.Cook) Becc.	27 (T)	VU	19	50
Senna polyphylla var. neglecta H.S.Irwin & Barneby	28	CR	78	60
Tillandsia x lineatispica Mez	29	N/A	23	20
Tolumnia prionochila (Kraenzl.) Braem	30	NT	66	20
Vachellia anegadensis (Britton) Seigler & Ebinger	31 (A)	EN	651	30
Vachellia anegadensis (Britton) Seigler & Ebinger	31 (VG)	EN	87	100
Varronia rupicola (Urb.) Britton	32	EN	931	30
Zanthoxylum flavum Vahl	33	VU	24	30
Zanthoxylum thomasianum Krug & Urb.	34 (T)	EN	44	100
Zanthoxylum thomasianum Krug & Urb.	34 (VG)	EN	487	60

† For plants which were given different conservation targets depending on the strata they occurred in, location are mentioned in brackets; Anegada (A); Tortola (T); Virgin Gorda (VG).

Table A2. Conservation features and conservation targets for threatened habitats.

Habitat	ID	Extend (km²)	Target (%)
Coastal evergreen shrubland	35	36.3	30
Mangrove	36	1.9	30
Upland evergreen forest	37	8.2	30
Salt pond	38	7.6	30
Semi deciduous gallery forest	39	0.5	30

Appendix 2

Table A3. Environmental Risk Surface: Intensity scores and influence distances.

| Threat	Impact	Impact score	Decay distance (m)	Comments
Agricultural areas (low impact)	Very low	10	100	Significantly low intensity agriculture
Agricultural areas	Low	33	100	Low intensity agriculture in the BVI
Airports (small)	Medium	66	100	Potential future expansions of airports imposed a larger threat level.
Airport (Tortola)	Medium	66	150	Potential future expansions of airports imposed a larger threat level.
Cement plant	High	99	300	Expanding boundaries, air pollution.
Desalination plant	Low	33	100	Unknowns range of impact from outflow pipe, high energy ocean currents assist to dissipate hypersaline water.
Developed land (roads and buildings)	Low	33	0	No impact outside borders.
Electrical plants (small)	Low	33	300	Oil spills, air pollution.
Electrical plants (large)	High	99	300	Oil spills, air pollution.
Garbage dump sites	Medium	66	100	Fire risk, air pollution.
Incinerator	High	99	600	Expanding boundaries, air pollution.
Large Hotels	Medium	66	10	Traffic.
Marina	Low	33	0	No impact outside borders.
Plant nursery	Medium	66	50	Potential introduction of invasive species or pests.
Proposed development in mangroves	High	99	0	Area with proposed development.
Quarries	High	99	150	Expanding boundaries.
Sewage treatment plant	Low	33	0	No impact outside borders.
Solid waste site	High	99	200	Fire risk.
Vehicle dump site	High	99	100	Expanding boundaries.
Water tank	Low	33	30	Small scale due to low population, but risk of future expansion.
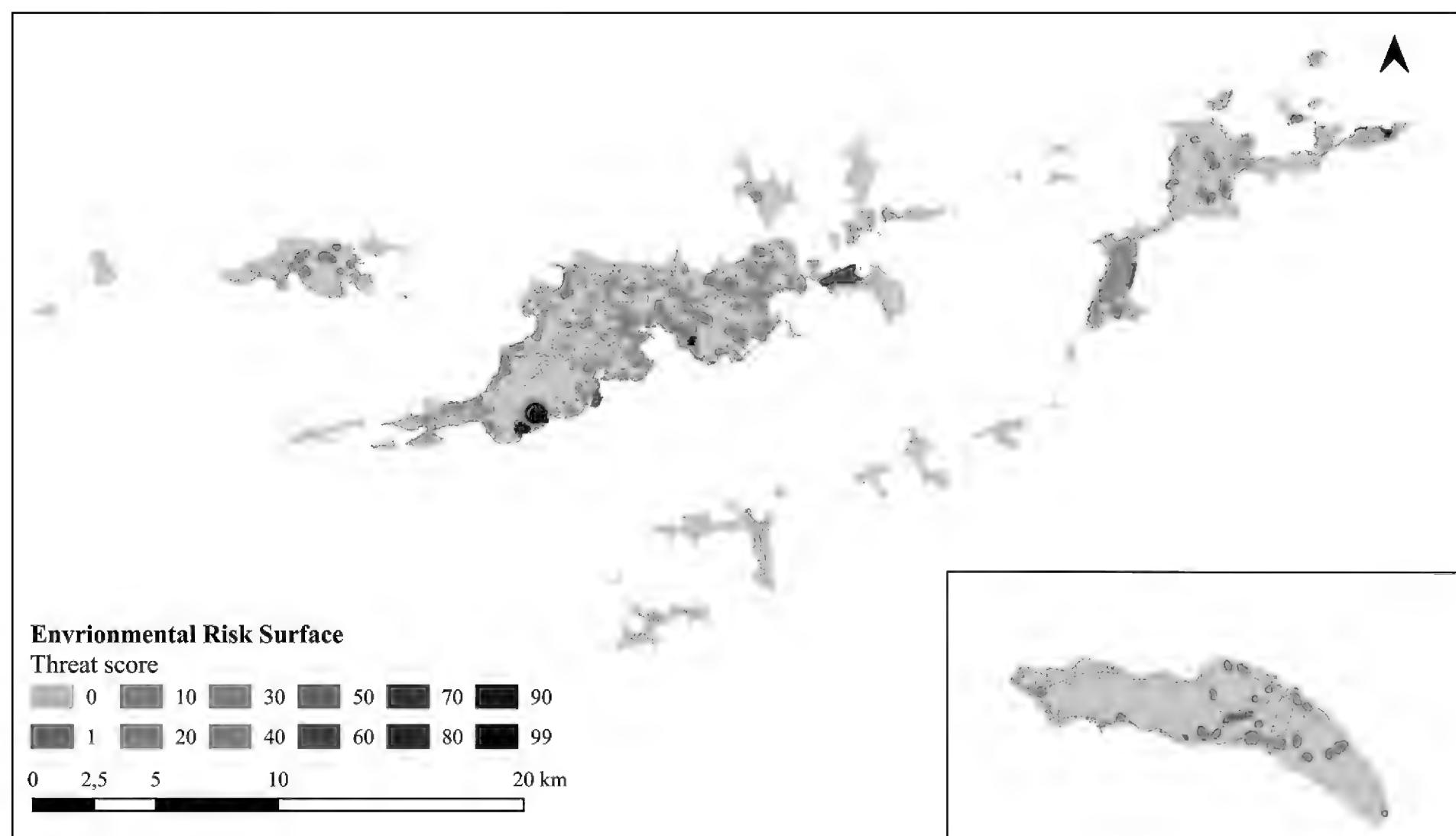
Figure A1. Environmental Risk Surface map over the British Virgin Islands.

Appendix 3

Table A4. Portfolio analysis for Plant Species of Conservation Concern.

ID[†]	Protected Areas System Plan			Main portfolios[‡]			Crown land portfolios		
	Plant records	Protected %	%-point gap	Plant records	Protected %	%-point gap	Plant records	Protected %	%-point gap
1	3	4	-46	45	54	4	12	15	-36
2	89	20	-20	305	68	28	193	43	3
3	3	18	-2	6	35	15	4	24	4
4 (A)	27	25	5	109	100	80	107	98	78
4 (T)	2	50	20	3	75	45	2	50	20
5	1	50	0	1	50	0	1	50	0
6	66	16	-4	366	89	69	194	47	27
7	5	39	-12	13	100	50	13	100	50
8	13	19	-1	55	81	61	25	37	17
9 (A)	12	67	47	18	100	80	18	100	80
9 (T)	0	0	-70	1	100	30	0	0	-70
10	23	100	40	23	100	40	23	100	40
11	35	100	0	35	100	0	35	100	0
12 (T)	10	59	-41	17	100	0	10	59	-41
12 (VG)	0	0	-50	147	87	37	115	68	18
13	109	36	16	232	76	56	157	52	32
14	15	8	-52	172	93	33	158	85	25
15 (A)	67	32	-8	212	100	60	201	95	55
15 (VG)	0	0	-100	4	100	0	1	25	-75
16	14	26	-4	53	100	70	14	26	-4
17	1	2	-68	48	100	30	36	75	5
18	57	97	-3	59	100	0	59	100	0
19	31	91	31	34	100	40	34	100	40
20 (T)	0	0	-100	1	100	0	1	100	0
20 (VG)	3	8	-32	32	84	44	32	84	44
21 (T)	4	19	-21	18	86	46	14	67	27
21 (VG)	0	0	-100	3	100	0	3	100	0
22	6	15	5	35	88	78	20	50	40
23	0	0	-10	15	94	84	0	0	-10
24	17	22	2	61	78	58	47	60	40
25	15	7	-3	150	73	63	107	52	42
26	17	16	6	81	76	66	61	58	48
27 (A)	1	10	-90	10	100	0	10	100	0
27 (T)	3	16	-34	10	53	3	3	16	-34
28	6	8	-52	78	100	40	72	92	32
29	4	17	-3	20	87	67	16	70	50
30	20	30	10	54	82	62	48	73	53
31 (A)	151	23	-7	651	100	70	637	98	68
31 (VG)	87	100	0	87	100	0	87	100	0
32	406	44	14	930	100	70	910	98	68
33	9	38	8	24	100	70	24	100	70
34 (T)	0	0	-100	43	98	-2	11	25	-75
34 (VG)	41	8	-52	475	98	38	169	35	-25
All[§]	1373	26		4736	90		3684	70	

† Strata in brackets; Anegada (A); Tortola (T); Virgin Gorda (VG).
‡ The Best Solution and SF100 portfolios reached the same conservation targets, and have therefore been grouped.
§ Number of plant records protected and their percentage fraction of all records within the analysis.

Table A5. Portfolio analysis for threatened habitats.

ID	Protected Areas System Plan			Main portfolios[†]			Crown land portfolios		
	Area km²	Protected %	%-point gap	Area km²	Protected %	%-point gap	Area	Protected %	%-point gap
35	7.8	22	-9	20.8	57	27	13.6	38	8
36	0.9	50	20	1.6	83	53	1.1	61	31
37	0.8	10	-20	3.5	43	13	1.6	20	-10
38	7.2	95	65	7.4	98	68	7.4	97	67
39	0.0	0	-30	0.3	55	25	0.2	30	0
All[‡]	16.7	31		33.6	62		23.9	44	

† The Best Solution and SF100 portfolios reached the same conservation targets, and have therefore been grouped.
‡ Area of habitats protected and their area percentage fraction of all threatened habitats within the analysis.

Table A6. Analysis of target achievement for all conservation features.

	Conservation features met (0/1)			Exceeded targets with ≥ 50%-point (0/1)		Target achievement (0/1)	
ID[†]	Protected Areas System Plan	Main portfolios	Crown land portfolios	Main portfolios	Crown land portfolios	Equal for all portfolios	Redundant coverage [‡]
1	0	1	1	0	0	0	0
2	0	1	1	0	0	0	0
3	0	1	1	0	0	0	0
4 (A)	1	1	1	1	1	0	1
4 (T)	1	1	1	0	0	0	1
5	1	1	1	0	0	1	0
6	0	1	1	1	0	0	0
7	0	1	1	1	1	1	0
8	0	1	1	1	0	0	0
9 (A)	1	1	1	1	1	1	1
9 (T)	0	1	0	0	0	0	0
10	1	1	1	0	0	1	0
11	1	1	1	0	0	1	0
12 (T)	0	1	0	0	0	0	0
12 (VG)	0	1	1	0	0	0	0
13	1	1	1	1	0	0	1
14	0	1	1	0	0	0	0
15 (A)	0	1	1	1	1	0	0
15 (VG)	0	1	0	0	0	0	0
16	0	1	0	1	0	0	0
17	0	1	1	0	0	0	0
18	0	1	1	0	0	1	0
19	1	1	1	0	0	1	1
20 (T)	0	1	1	0	0	1	0
20 (VG)	0	1	1	0	0	1	0
21 (T)	0	1	1	0	0	0	0
21 (VG)	0	1	1	0	0	1	0
22	1	1	1	1	0	0	1
23	0	1	0	1	0	0	0
24	1	1	1	1	0	0	1
25	0	1	1	1	0	0	0
26	1	1	1	1	0	0	1
27 (A)	0	1	1	0	0	1	0
27 (T)	0	1	0	0	0	0	0
28	0	1	1	0	0	0	0
29	0	1	1	1	0	0	0
30	1	1	1	1	1	0	1
31 (A)	0	1	1	1	1	0	0
31 (VG)	1	1	1	0	0	1	0

ID[†]	Conservation features met (0/1)			Exceeded targets with ≥ 50%-point (0/1)		Target achievement (0/1)	
	Protected Areas System Plan	Main portfolios	Crown land portfolios	Main portfolios	Crown land portfolios	Equal for all portfolios	Redundant coverage [‡]
32	1	1	1	1	1	0	1
33	1	1	1	1	1	1	1
34 (T)	0	1[|]	0	0	0	0	0
34 (VG)	0	1	0	0	0	0	0
35	0	1	1	0	0	0	0
36	1	1	1	1	0	0	1
37	0	1	0	0	0	0	0
38	1	1	1	1	1	0 [§]	1
39	0	1	1	0	0	0	0
Sum Plant Species	12	34	27	14	4	8	10
Sum habitats	2	5	4	2	1	0	2

† Strata in brackets; Anegada (A); Tortola (T); Virgin Gorda (VG).

‡ For conservation features within the main portfolios, that experienced a higher coverage even though conservation targets were already adequately achieved in the current Protected Areas System Plan.

§ Almost equal %-point gap.

| The endemic *Zanthoxylum thomasianum* (ID:34) was one plant record short of reaching its target of a 100% in Tortola. However, it is expressed as if all records on Tortola were covered within the 'Best solution' and 'SF100' portfolios, due to the gap being made up of a single plant record, is considerably small, and it being outside of the TIPAs, and thus not possible to conserve within the means of this analysis.

Supplementary material 1

Portfolios - Anegada

Authors: Michalla Alicja Dolata, Nancy Woodfield-Pascoe, Thomas Heller, Michele Dani Sanchez, Sara Bárrios, Steven R. Schill, Patrik Karlsson Nyed, Martin Allen Hamilton, Keith Grant, Colin Clubbe, Bo Dalsgaard

Data type: pdf

Link: https://doi.org/10.3897/natureconservation.55.116844.suppl1

Supplementary material 2

Portfolios - Tortola

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Data type: pdf

Link: https://doi.org/10.3897/natureconservation.55.116844.suppl2

Supplementary material 3

Portfolios - Virgin Gorda

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